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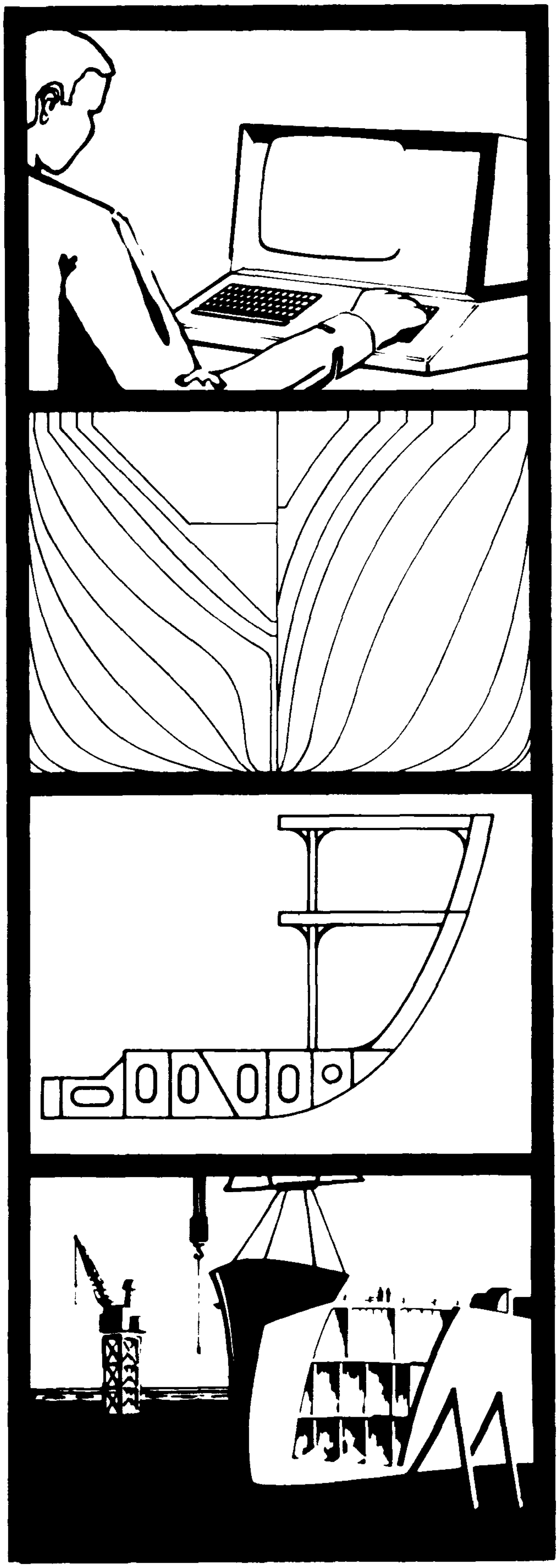

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PHOTOGRAMMETRIC THREE-DIMENSIONAL DIGITIZING OF PIPING ARRANGEMENT SCALE MODELS FOR COMPUTER INPUT

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ABSTRACT

In July 1976 MarAd, in cooperation with Todd Shipyards Corporation, Seattle Division, published a National Shipbuilding Research Program report entitled "Photogrammetry in Shipbuilding". Efforts put forth in the conduct of that project represented the U.S. shipbuilding industry's first exposure to photogrammetry, the science of obtaining two- and three-dimensional measurements from photographs. Included within that report were detailed descriptions of four surveys conducted under real shipyard conditions. One of these employed photogrammetry to produce a composite drawing of a ship's machinery space using photographs of its design mode. This initial work allowed MarAd to develop the foresight that digital photogrammetry could be an ideal means by which the geometry of distributive systems, as portrayed on inherently interference-free design models, could be put directly into a computer and "married" to already developed automated detailing systems.

In the followon project described herein, photogrammetric procedures and basic computer programs were developed which would allow piping geometry and events to be expressed in terms of coordinates in a ship's coordinate system; i.e., in precisely the same form that input to computerized pipe detailing systems must be presented. The fact that piping geometry can be "lifted" photogrammetrically from a design model is not so striking until one considers the alternative methods. Only then does the practicality of photogrammetry become clear. Without extreme measures, pipe lengths and in-line locations of pipe events can be determined with a typical accuracy of + ½ inch or better, onboard from photographs of a 1:15 design model.

The excerpts contained herein are from a forthcoming publication by Todd Pacific Shipyards Corporation, Seattle Division, in cooperation with the Maritime Administration for the National Shipbuilding Research Program.

Design models (or engineering models) are inherently interference-free and are built' by designers who work directly from system diagrammatics. They do not first prepare costly and time consuming system- and composite-arrangement drawings. Thus, shipbuilders in Europe and Japan are striving by different means to perfect cost-effective methods for obtaining the following directly from design models:

o pipe-piece details,

o material lists, and

0 assembly instructions.

The subject research discloses that marrying three existing disciplines, each already proven in industry, achieves the desired objectives; see Figure 1-3 attached.

The other excerpts contained herein are Chapter 2 - Concjusions and Appendix E - Details of the Developed Photogrammetric System.

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R&D.Program Manager &
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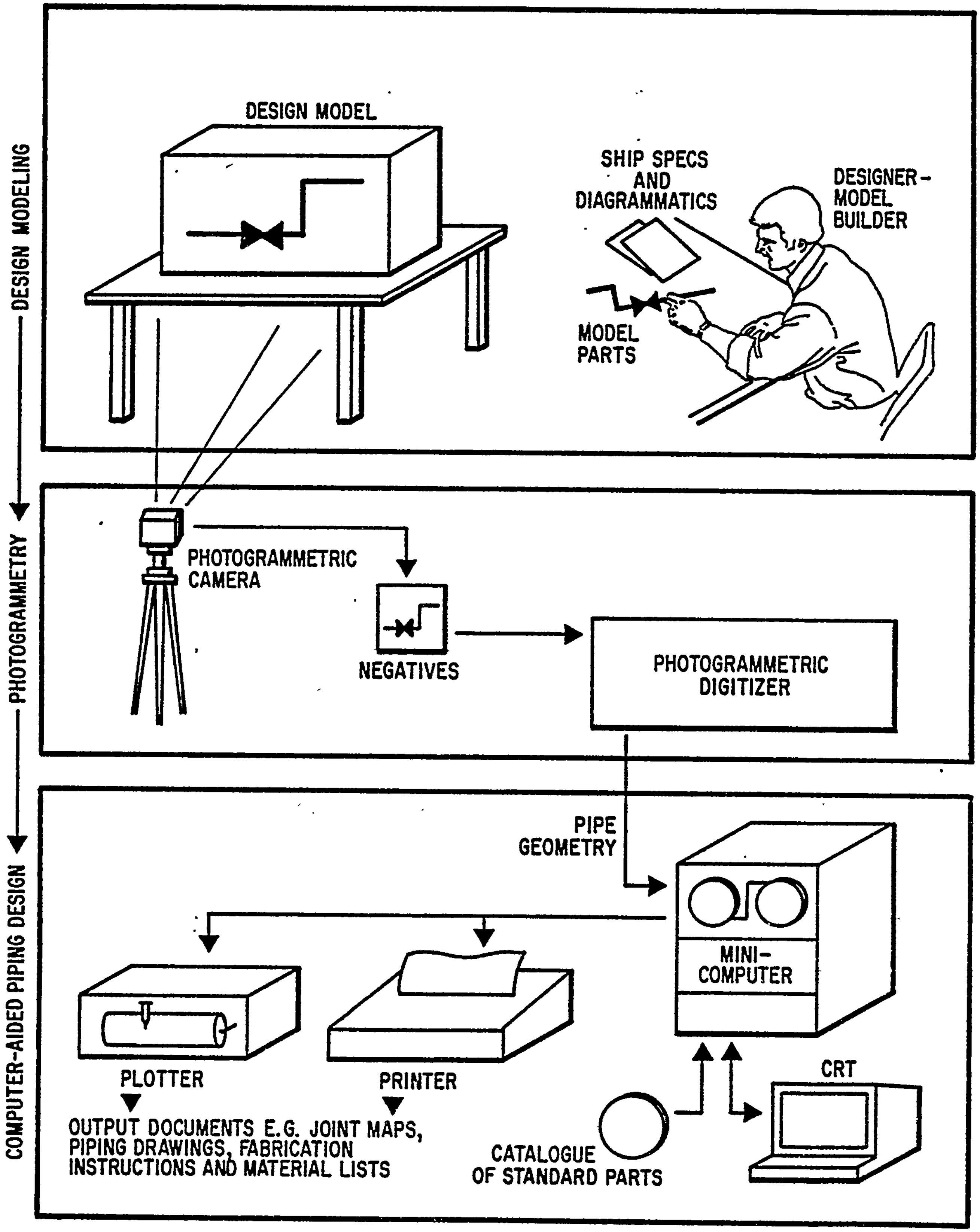


FIGURE 1.3 : The Marriage of Design Modeling, Photogrammetry and Computer-Aided Pipe Detailing Systems.

2. CONCLUSIONS

Photogrammetry does provide a productive means by which dimensions may be "lifted" from design models. The practical application of photogrammetry relies to a large extent upon processes peripheral to photogrammetry per se. Hence, it is appropriate to identify all related functions and to state conclusions with respect to each.

2.1 Model Building Technique

Distributive systems of a model can be productively dimensioned by photogrammetry only if forethought is given to the manner in which the model is constructed and presented.

2.1.1 Model Sectioning

To facilitate "photographic access" to the interior of a model, the model must be built on multiple model bases. Divisions atmidships, bulkheads and decks are desirable, although any other divisoning scheme such as along outfitting blocks is suitable. Sub-divisioning so that overheads can be removed and photographed separately is also a requirement. See also paragraph 2.1.3.

2.1.2 Minimal Use of Plexiglass

To minimize geometric distortions and reflections which occur on photographs "viewed". through plexiglass,. the amount of plexiglass used must be held to a minimum. Where plexiglass must be used, cutouts should be employed to the greatest possible extent. See also paragraph 2.1.3.

2.1.3 Removable Components

Wherever it is practical, machinery components and platforms should be removable. This also permits the distributive systems to be photographed with fewer obstructions and/or distortions and reflections.

2.1.4 Color Coding

Color coding of the various distributive systems is essential to any photographic documentation program. Color coding is particularly beneficial to photogrammetric work because black and white photographs may be employed. These are readily interpreted owing to tonal differences rendered by the color coded distributive systems.

2.1.5 Finishes

Surface finishes of structural, machinery and distributive system components should not be highly reflective. Dull finishes are preferred because they reflect light in a diffuse manner, thereby reducing "glare" on the photographs.

2.1.6 Tags

Tags placed on machinery pieces and distributive systems are sometimes helpful when interpreting photographs. However, they should not be so bulky as to obscure portions of distributive systems. In particular, tags on pipes must be completely adhered to the pipes. Bulky tags attached tangent to pipes oftentimes obscure edges of the pipes.

2.1.7 Representation of Piping

Because procedures developed for photogrammetric dimensioning of distributive systems models are quite general, piping may be represented in the model true-to-scale or by the centerline method. For photogrammetric purposes the centerline presentation is the most desirable because it presents the least interference with photographic viewing into the model. Trends in modeling technique indicate, however, that the centerline method of portrayal is not likely to be used with frequency.

2.2 Photography

2.2.1 Preparation of the Model

Model sections require very little preparation in advance of taking the photographs. Preferably, a few points of known (or partially known) ship's coordinates are fit with small adhesive bull's-eye targets to permit accurate identification later on in the digitizing work. It is also desirable to place a few additional targets at dispersed, easily viewed yet arbitrary locations. These permit accurate matching of different photographic views of the same model section (see paragraph 2.2.2).

2.2.2 Procedures

The photographic process should not require that the model be brought to a photographic laboratory. Instead, the camera(s) should be taken to wherever the model may be situated. Procedures for setting up the model and for taking the pictures should be so simple that they can be readily implemented without elaborate preparation.[1] This includes positioning of the camera and lighting.

Stereophotography of model sections is required so that the photographs can be viewed in a stereodigitizer. The camera may be mounted upon a tripod or it may be hand-held. The base-distance ratio, i.e. the distance between camera positions relative to the distance from the camera locations to the object, must be small. Wide separations between cameras cannot be employed because stereoscopic coverage of vertical pipes is lost owing to their cylindrical shapes.

[1]Such a scheme is described in Appendix E.

Pairs of stereophotographs must be taken from widely different vantage points. This virtually eliminates chances for "lost detail". That is, piping detail which may be obscured on one pair of photographs will likely be visible on some other pair taken from a different vantage point.

It is also desirable to take the stereophotographs such that the camera ares are inclined relative to the model section. This also facilitates viewing detail which might otherwise be obscured if, for example, the camera axes were in or near a plane containing a number of horizontal pipe runs.

Lighting-is best provided by electronic strobes aimed away from the model to nearby walls and the ceiling. This produces uniform "bounce" lighting of the model which minimizes "glare" and shadows on the photographs.

Ordinary black and white panchromatic emulsion is entirely suitable for photogrammetric work. However, color snapshots should also be taken for reference when there is an occasional need for aid in interpreting the black and white photographs.

2.2.3 Hardware

A single, variable focus photogrammetric camera is best suited to model photography. This type of camera (as opposed to a fixed focus double camera) provides far greater flexibility for accommodating varying sizes of model sections. It is also more portable and easier to handle while taking pictures. The same type camera is also well suited to other shipyard tasks such as dimensioning large steel units.

Electronic strobes are needed to provide artificial lighting of the model. Because bounce lighting is preferred and also because the camera may be hand-held, the combined output of the strobes must be much greater than would ordinarily be required for other types of photographic work. A combined total output capability of at least 1,200 watt-seconds in a single flash is desirable.

2.3 Preparation for Stereodigitizing

It is felt that the operator of the stereodigitizer should not be burdened with non-photogrammetric selection and decision making functions, lest his productivity on the digitizer be drastically reduced. Two pre-digitizing preparations serve the purpose of maximizing productivity at the digitizing stage.

2.3.1 Photo Enlargements

Occasionally, for personal orientation, the operator of the stereodigitizer needs to refer to an overall view of the model. A black and white enlargement of one of the two photographs set in the stereodigitizer serves this purpose. Such enlargements also serve as a medium on which detail to be digitized can be annotated.

2.3.2 Transparent Overlays

Detail to be digitized is preferably annotated on transparent overlay(s) of the photographic enlargement instead of on the enlargement itself. This procedure leaves the enlargement in its original form to serve its first intended purpose (paragraph 2.3.1). It is also possible to use more than one overlay if a single overlay should become too cluttered or if it is desired to separate types of detail to be digitized.

2.3.3 Precomputed Stereodigitizer Settings

Of two basic types of stereodigitizers that can be used for dimensioning design models (paragraph 2.4.1), one requires manual orientation of one photograph of a stereopair to the other. This is a difficult time-consuming process, even for an experienced photogrammetrist. It is state-of-the-art, however, to analytically calculate dial settings for any stereopair in advance of presenting the photographs to the stereodigitizer. This requires measurement of images of corresponding points on each photograph (usually on a monocomparator). These measurements are then computer-processed to produce stereodigitizer settings which may be dialed into the instrument as an initial step before stereodigitizing of *a* stereopair commences. Although this process of precalculating settings is theoretically unnecessary, it is required as a practical matter for productivity reasons.

2.4 Stereodigitizing

2.4.1 Hardware

Two types of photogrammetric instruments are suited to the task of dimensioning from models. The first is an analogue stereoplotter. However, only analogue stereoplotters having the following attributes may be employed:

- accommodation of a wide range of focal lengths
- large height range
- short camera separation capability

[1]Analogue stereoplotters are intended primarily for topographic mapping from aerial photographs. But, some have liberal mechanical ranges which render them suitable for some non-topographic tasks.

- digital output in all three axes

A computer-controlled stereoplotter may also be employed. Relative to the analogue instrument its major advantages are:

- by virtue of the computer-aided stereoscopic viewing, there are no practical limitations that are otherwise imposed by mechanical functions of analogue stereoplotters, thus permitting greater freedom in the picture taking process since there is no longer a concern for exceeding mechanical limitations of an analogue instrument.

- precalculation of instrument settings (paragraph 2.3.3) is not necessary since the on-line computer handles this task

2.4.2 Procedures

It was found that having designed a general dimensioning scheme, such as outlined in Appendix E, stereodigitizing procedures are very simple. It is not necessary to follow a complicated hierarchical system in order ***to*** gather data needed to ultimately construct the paths of pipe runs and locations of in-line events (see paragraph 1.5). But, it does serve to avoid confusion and omissions of data if pipe runs and pipe events are separately digitized. Such separation does not imply, however, separate setups of the stereodigitizer.

The digitizing scheme developed for this project required that random points on the surface of each straight-line pipe segment be digitized. Once all pipe segments within a given stereomodel were digitized, one or two points on each pipe event were digitized. All such data were later processed through a series of computer programs to arrive at the desired end products: coordinates defining the paths of the pipe centerlines and coordinates fixing the centerline locations of pipe events.

2.5 Data Processing

Data processing steps and computational algorithms depend almost entirely upon how the preparation and stereodigitizing efforts are designed. The scheme developed for this project is describing in detail in Appendix E. This particular procedure dictated that the computational flow proceed in the following sequence:

- conversion of digitized coordinates to ship's coordinates
- **sorting data belonging to identical features but** digitized in different stereomodels
- calculation of *a* centerline for each pipe *segment* by fitting a cylinder to digitized points on *the* pipe surface
- calculation of coordinates of bend intersection points by intersecting computed centerlines of adjacent pipe segments
- calculation of centerline locations of each pipe event by projecting a line through a digitized point on the event, perpendicular to the previously computed centerline of the corresponding pipe segment.

2.6 Evaluation of End Results

2.6.1 Accuracy

By virtue of having computed coordinates of bend intersection points it is a simple matter to calculate the space distance between adjacent bend intersections. Such calculated distances were compared to corresponding distances as physically scaled on the model. Over all distances compared the average difference was 8.4 mm (0.33 inch) and the maximum difference was 40.0 mm (1.57 inch) on board.

A similar scheme was employed to check computed locations of pipe events; i.e. their locations distance-wise from the nearest bend intersection. The average difference was 12.6 mm (0.50 inch) with a maximum of 28.0 mm (1.10 inch).

It was further concluded that the photogrammetric results were far more reliable than physical measurements of the model. Initial comparisons of pipe lengths and locations of pipe events revealed an extraordinary number of blunders in the physical measurements. These blunders almost always resulted from the inability to directly measure a scale model by hand. Although this is partly due to congestion of model detail, the principal imposing factor is that it is not possible to take measurements directly to pipe or event centerlines. Instead, one is constantly faced with taking alternate distances and then modifying these to account for offsets, pipe radius, etc. Perhaps the greatest detraction of all is the inability to physically find bend intersection points, particularly for other than 90-degree bends. Hence, accuracy figures given above are likely to be pessimistic.

2.6.2 Completeness

If a general digitizing scheme such as the one described in Appendix E is employed, virtually all piping detail can be extracted from the model. This is partly because digitizing is performed within stereo pairs of photographs taken from several different vantage points. This serves to minimize data loss caused by obscurations within the model which often occur if only photographs from one vantage point are used. Secondarily, because it is necessary only to digitize random points ***on*** a pipe's surface (and later fit a cylinder to these points), it is necessary only to be able to see portions of a pipe's surface in any given stereo pair. Also see paragraph 2.2.2.

2.6.3 Cost

Paragraph E.3.1 describes and illustrates the Hitachi model which was used for the final test of the developed process. The six model sections obtained from Hitachi incorporated approximately 230 pipe segments[1] and 160 pipe events. A general elevation view of the six model sections fully assembled is shown in Figure 2.1.

Extrapolation of costs associated with photographic, stereo-digitizing and data processing tasks (for parts of the model) revealed that piping geometry for all six model sections could be produced for $12,100. Utilization of a more productive computer controlled stereodigitizer (see paragraph 2.4.1) could reduce the cost nearly 25%. These costs include burdened labor and equipment useage but not G&A or profit.

E. DETAILS OF THE DEVELOPED PHOTOGRAMMRTRIC SYSTEM

E.l Desirable System Attributes

In the early stages of the project there were no preconceived ideas as to the best photogrammetric approach to dimensioning from models. A purely analytical process was considered as was a stereo system; both were described in the Interim Report. In evaluating possible solutions, a list of desirable characteristics was prepared. Some of these should apply to any dimensioning ***system;*** photogrammetric or otherwise.

a. The system and procedures should basically be the same regardless of whether the model is true-to-scale or wire and disc.

b. Drastic changes in current model building techniques should not be required.

[1]A pipe segment is generally considered to be any straight line run between two bends or a bend and a nozzle.

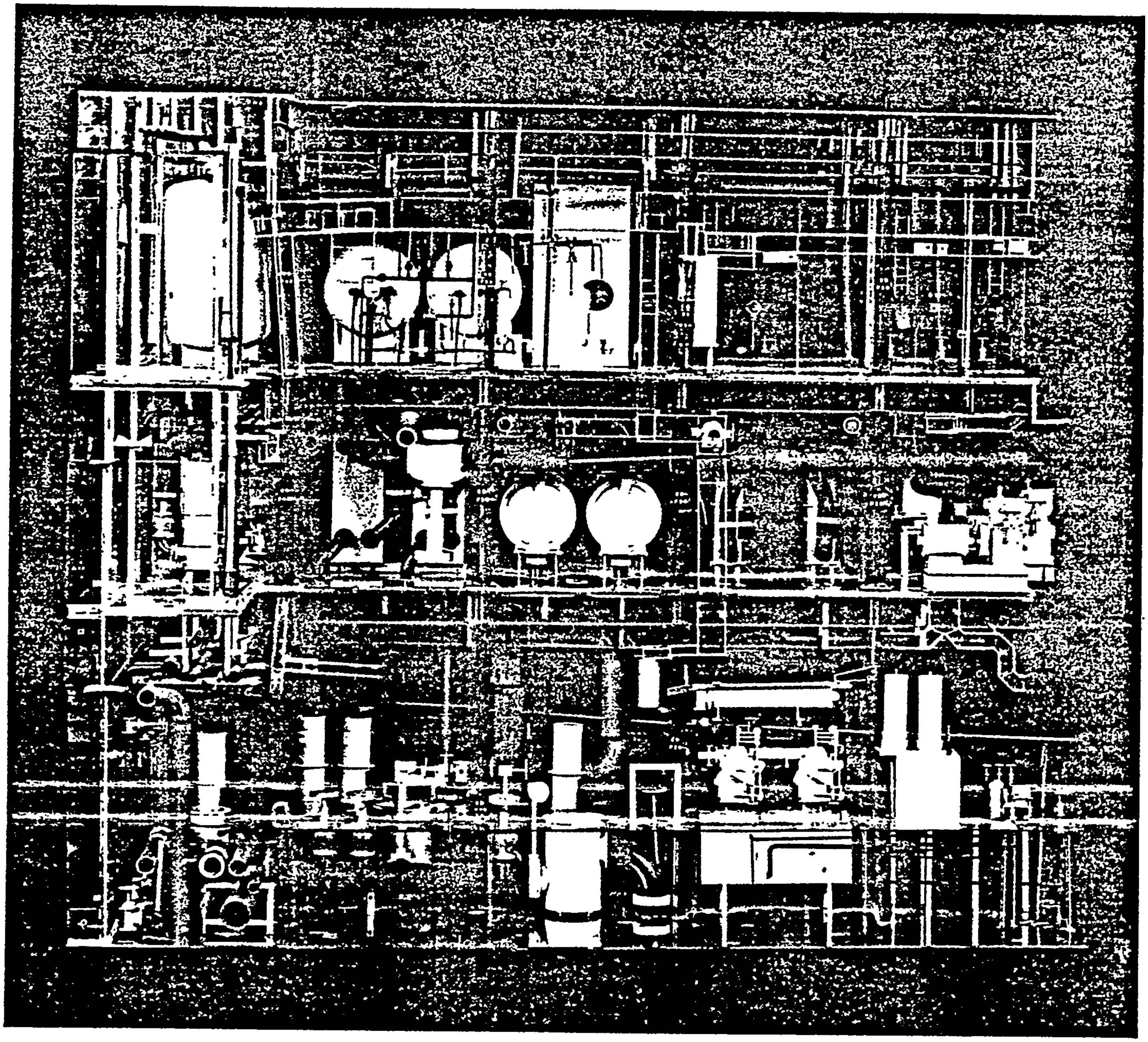


FIGURE 2.1: Six Fully Assembled Sections of the Hitachi Model. The entire model (not all obtained for the project) is comprised of 25 sections portraying the entire machinery space of an 18,930 DWT container ship. The particular sections shown represent the forward starboard portion of the machinery space from the tank top to the upper deck. These were used for the final test of the developed photogrammetric system. View is inboard looking outboard.

C. Specially built photogrammetric hardware should not be required.

d. The camera must have the ability to be focussed over a range of photographic distances.

e. Extensive preparation of the model should not be required.

f. Extreme care in positioning the camera or the model should not be required.

g. Black and white photographs should be used if it is possible to do so without seriously affecting productivity.

h Gathering of raw data (i.e. taking photographs) should be fast so as not to interfere with the use of the model by designers, planners, etc.

i. Digitizing from the photographs should be simple procedurally so that an expert photogrammetrist need not be employed.

j. The digitizing instrument should not be significantly limited in photographic focal length, allowable base between camera stations and lack of parallelism between optical axis of adjacent photographs.

k. Coordinate data produced by the system must be of sufficient accuracy so as *to* be compatible with manufacturing and installation needs.

1. The data must be formattable so as to be compatible with existing computer-aided pipe detailing and fabrication programs.

m. If possible, photogrammetric equipment should also be usable for other shipyard measurement tasks such as dimensioning large steel units.

E.2 Basic Conclusions Regarding the System

It was ultimately concluded that the best overall solution would be a stereo system in which the stereodigitizer was of the computer controlled variety. It was also concluded, however, that it was not possible as *a* practical matter to directly digitize data needed by automated pipe detailing systems, i.e. pipe centerlines, bend intersection points and centerline locations of pipe events. This led to the final conclusion that these data would have to be determined indirectly by manipulating data which could be more readily digitized. At this juncture preliminary procedures were conceived and testing of these commenced. Procedures as well as hardware ultimately employed are described in the following paragraphs.

E.3 The Models

E.3.1 Descriptions

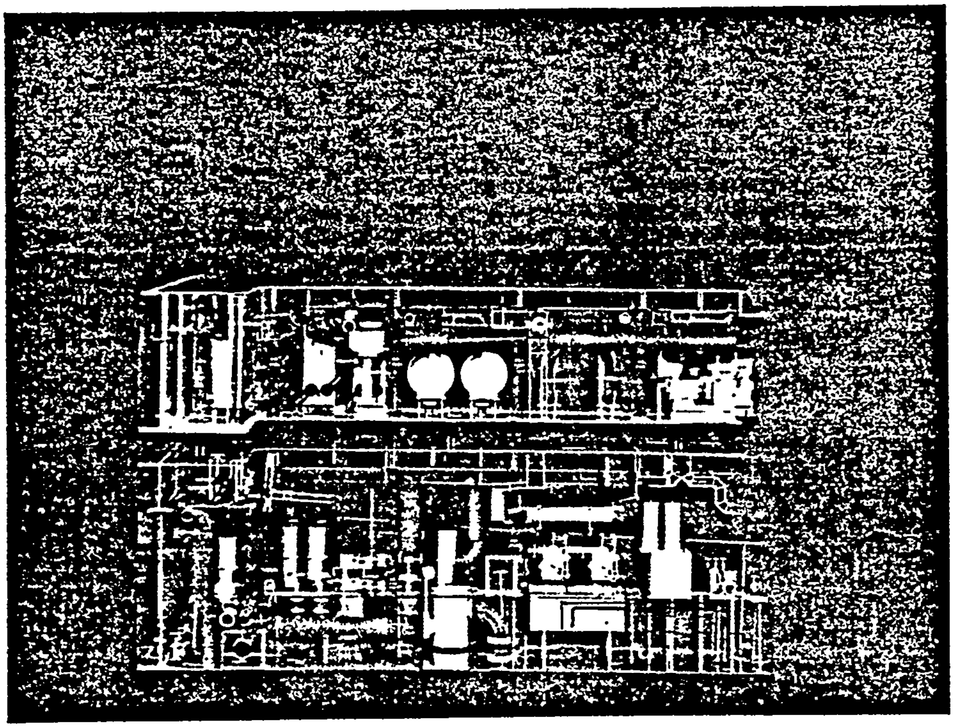
Initially experiments were conducted with a 4x2x2 ft. section of a floating nuclear power plant loaned to the project by Offshore Power Systems ("OPS") of **Jacksonville,** Florida. Work with this model allowed procedures to be tested and modified. Experimental stereodigitizing also provided data needed to test computer programs being prepared for the reduction of digitized data to coordinates of bend intersection points and centerline locations of pipe events.

While this experimental work was in process, arrangements were made with Hitachi Shipbuilding and Engineering Company, Ltd. to obtain portions of one of their design models of a ship's machinery space. It was deemed desirable to perform final tests of the photogrammetric system on a Hitachi model because of Hitachi's level of development in model engineering. Many of the desirable model building techniques set forth in paragraph 2.1 are state-of-the-art at Hitachi, particularly sectionalization.

Model sections obtained from Hitachi were from a 25-sectton 1:15 scale model of the machinery space for a 18,930 DWT container ship. The entire model measured 1.8 m in length, 1.8 m in breadth and 1.2 m in height. Three deck levels representing the forward starboard side of the model were obtained from Hitachi. Each deck level is sectionalized such that it is self-contained and may be further separated into two pieces comprising piping hung from the overhead and machinery and piping related to the deck below. Hence, a total of six model sections were actually obtained. Figures E.1 and E.2 illustrate how the model is sectionalized. Figure 2.1 shows all six model sections fully assembled.

E.3.2 Preparation of the Hitachi Model

In the course of building models it is customary for a regular reference grid to be fit, as a minimum, upon the model base. On the Hitachi model the grid system is scribed into the plexiglas of every deck and overhead and on large vertical surfaces as well. The grid spacings correspond to 1 m water lines, 1 m buttock lines and a 0.8 meter frame spacing. To provide the photogrammetric solution with an absolute shipboard reference, selected grid intersections of each model section were fit with a few simple targets so that these "known" locations would be readily identifiable on the photographs. Two types of targets were employed but both satisfactorily served the same purpose. One was a self-adhesive (peel-off backing) target having an annulus-like bull's-eye upon a black background. The second type target was merely a reinforcing ring normally used to reinforce punched holes in paper. The ring actually only served to identify a grid intersection - grid lines within the ring were clearly visible on all photographs. Each type target was hand lettered with the ship's coordinates of the grid intersection to which the target was attached. This was done merely as a matter of convenience. Both types of targets are shown in Figure E.3.



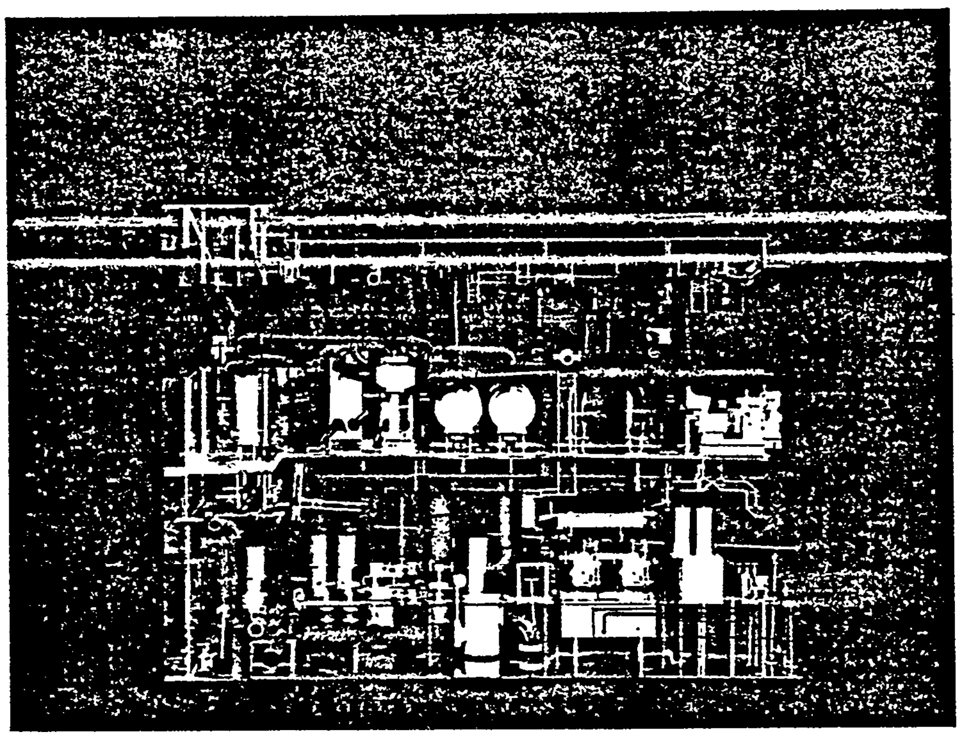
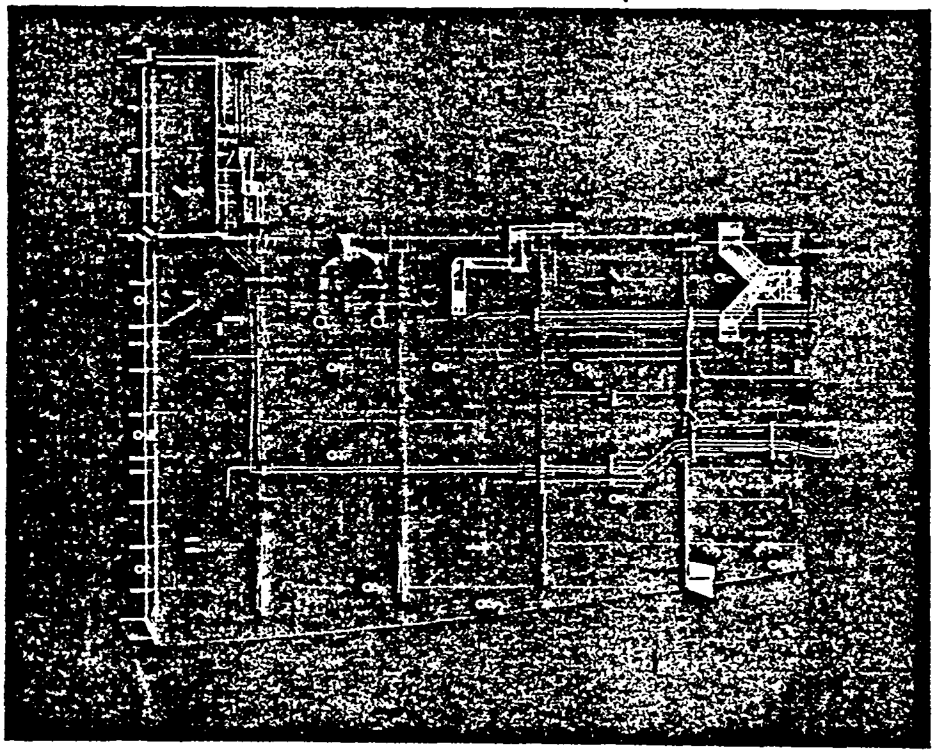


FIGURE E.1: Illustrating Sectionalization of the Hitachi Model. The upper picture shows how the model is sectioned horizontally through a deck. The particular split shown is through the third deck. The lower picture shows how the overhead below the second deck can be removed. Such sectionalization is standard between all deck **levels.**



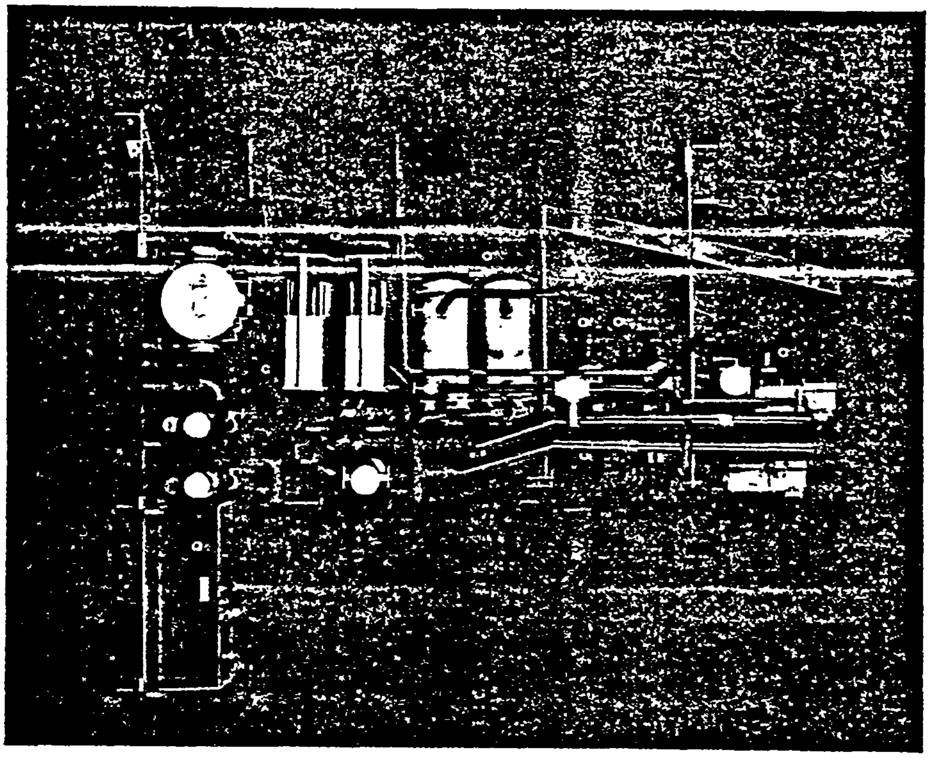


FIGURE E.2: Illustrating Division of the Hitachi Model Between Two Deck Levels. The upper picture is of an overhead (as if viewed from below). The lower picture is of the deck below (as if viewed from above). Particular sections shown lie between the second and third decks.

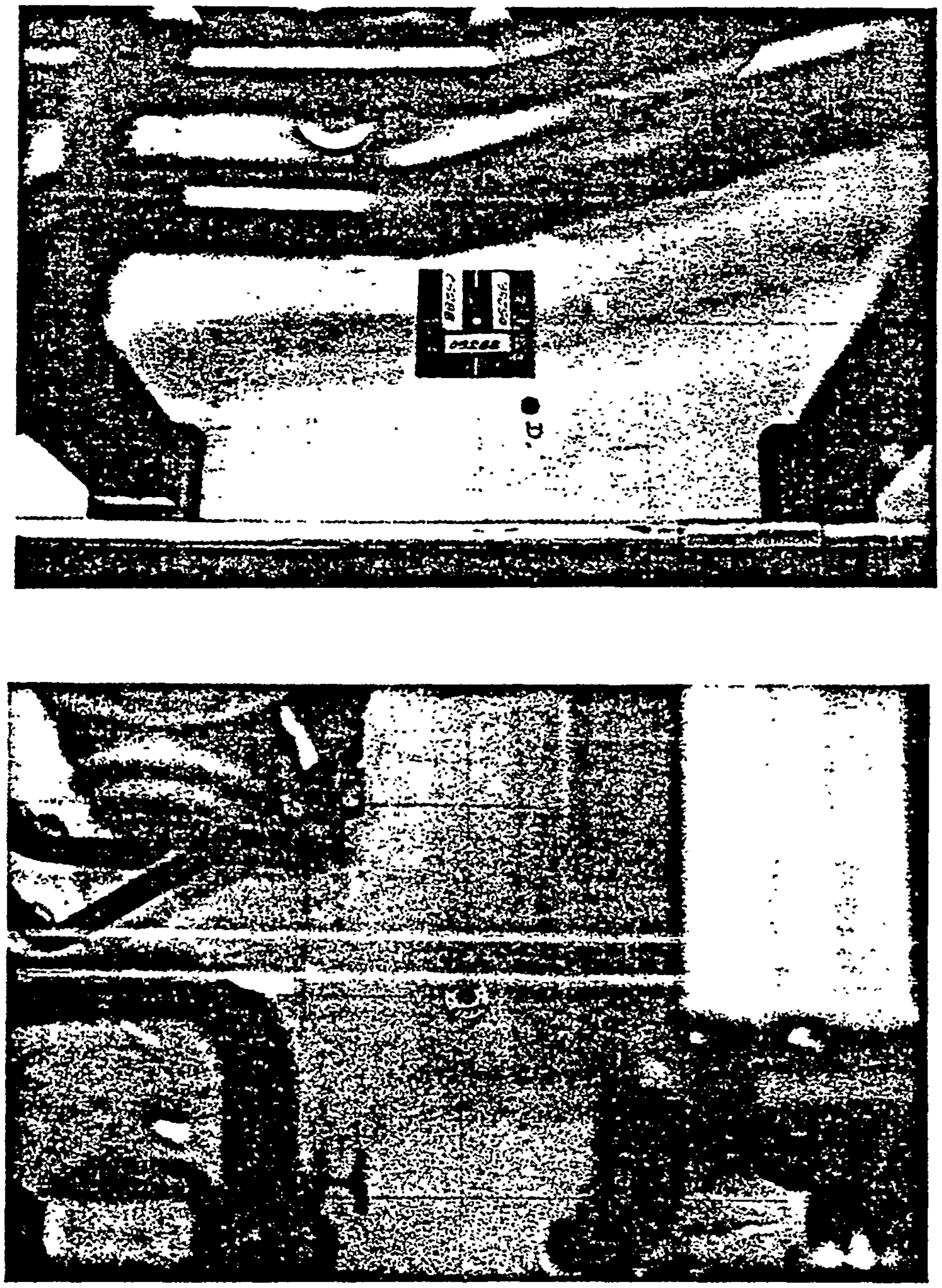


FIGURE E.3: Targets Signalizing Locations of Known Ship. Coordinates. The target shown in the upper illustration has a peel-off back which exposes a pressure sensitive adhesive. Registration marks are aligned with grid lines scribed on the model. In the lower figure an ordinary reinforcing ring circles a grid intersection which has been filled with red pencil. Both types of targets satisfactorily served the same purpose.

As will be seen later, several different photographic views of each model section are desirable. In order to accurately "match" these views to one another in the data processing phase, a few additional "tie-in" targets should be placed on each model section at well distributed locations which are likely to be seen in all photographic views. Targets placed at grid intersections can serve this purpose too, but oftentimes these cannot be seen in more than one or two views. Hence, the need for the extra "tie-in" targets. Such targets were not used on the Hitachi model but only because small discrete markings on the model served the same purpose.

To facilitate handling of a given model section for the photographic effort, the section was temporarily attached to a stiff board by means of small bolts. This allowed the section to be tilted and rotated while maintaining its rigidity. See paragraph E.4.3.

E.4 Photography

E.4.1 The Camera

All photographs of the OPS and Hitachi models were taken with the researcher's Wild P31 Universal Terrestrial Camera pictured in Figure E.4, but with the camera body removed from its mount. This particular camera was employed because of its ready availability. Nonetheless, compared to most other photogrammetric cameras, it is reasonably well suited to close-up photography of models. A similar camera manufactured by the Zeiss Jena works[1] would perhaps be better suited owing to its somewhat greater depth of field. Both the Wild and Zeiss cameras mentioned are characterized by virtually distortion

[1]The UMK 10/1318, sold in the U.S. through the Zena Company; see Appendix F.

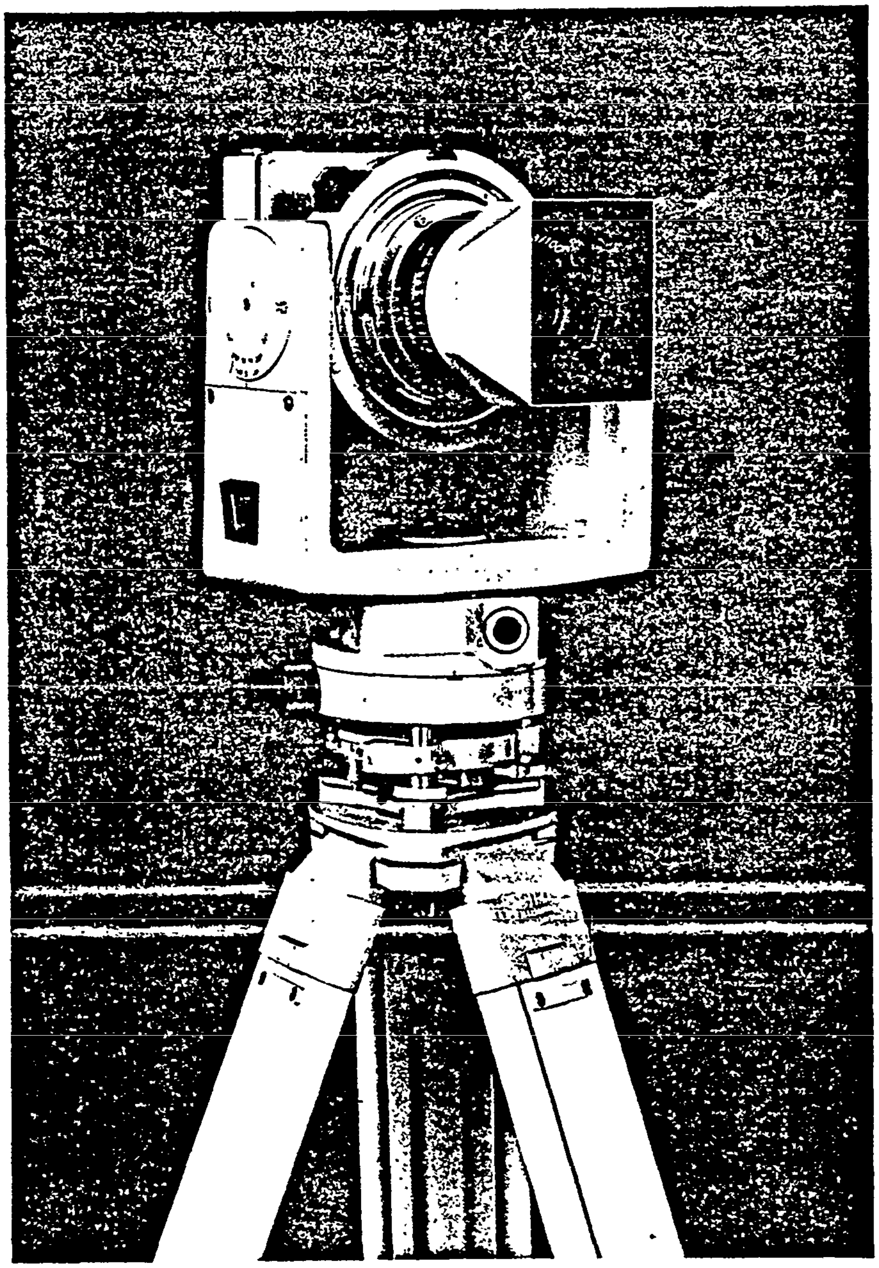


FIGURE E.4: The Wild P31 Universal Terrestrial Camera. This particular camera accepts single frames of glass or film, is focussable over a range of photographic distances and has a distortion free lens. The camera body may be removed from the yoke mount for hand-held use.

free lenses and their ability to accept glass plates *as* well as film for recording the imagery. Glass plates were used throughout this project because of their desirable dimensional stability. But, a large volume of production work could dictate the use of film for reasons of expense, ease of handling and storage.

E.4.2 Camera/Model Geometry

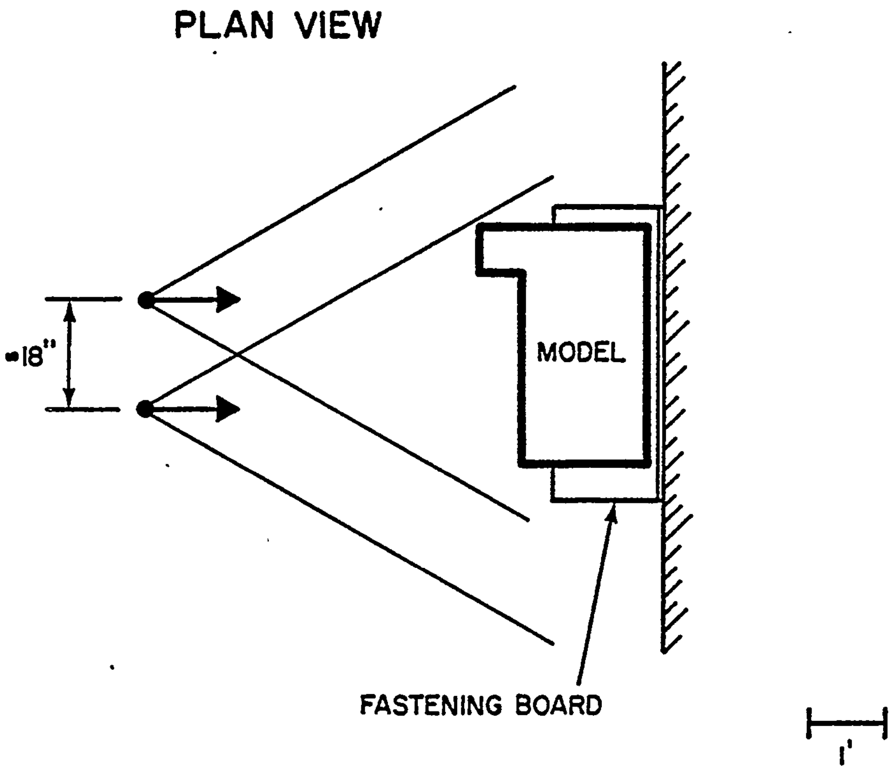
Rough calculations performed in advance indicated that a reasonable setup of camera stations relative to the model could be such that a single stereopair[1] would cover an entire model section. Basic tradeoffs considered were decreasing the camera-to-object distance for greater accuracy but with an increase in the number of photographs to expose and reduce owing to depth of field limitations at shorter ranges.

The geometry of the final setup is shown in Figure E.5. Two important additional considerations are incorporated in the plan shown:

a. The model is tilted so as to avoid as much hidden piping detail as possible. If photographs are taken with the camera axis in a plane parallel to the deck, piping in the foreground usually obscures piping in the background. This is because pipes are often run in common horizontal planes, particularly when hung from an overhead.

b. The distance between camera stations is smaller than desirable from an accuracy point of view. But, as a practical matter, the distance is limited by the need to digitize vertical piping in the foreground while viewing such pipes stereoscopically in the stereodigitizer. If the camera stations are too far apart, the left hand exposure will image the left side of a vertical pipe and the right hand exposure will 'image the right side of the pipe. Absence of common images on the two photographs renders it impossible to view such pipes stereoscopically and, therefore, digitize them.

[1] One photograph taken from each of two adjacent camera stations such that the **optical** axes of the two photographs are nearly parallel.



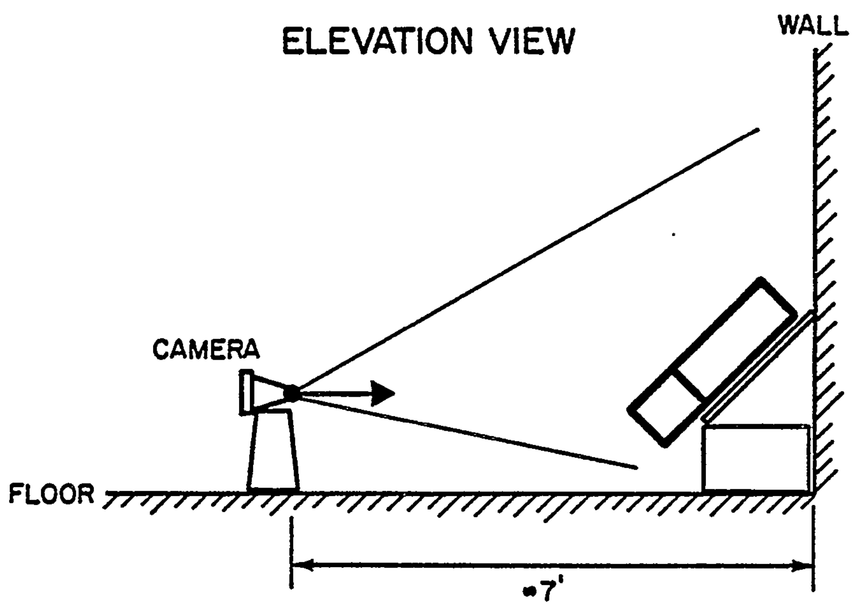


FIGURE E.5: Camera/Model Geometry. Trade-offs which must be considered are photogrammetric accuracy, number of photographs and depth of field, The model is tilted to avoid obscurations of the most distant (from camera) detail by detail in the foreground. A single camera was slid between camera stations to obtain the indicated exposures.

E.4.3 Procedures

Once a model section is attached to the fastening board it is set up as shown in Figure E.5. A picture (black and white) is taken from one of the indicated camera stations. The camera is then slid sideways to the adjacent camera station from which the second photograph of the stereopair is taken. The model section, still attached to the fastening board, is rotated 90 degrees and another stereopair is exposed. This process is repeated four times so that the model section is photographed from all four "sides".[1]

Figure E.6 illustrates the rotation process for the model section shown at the bottom of Figure E.2. Not shown in Figure E.6, however, are markings on the wall behind and around the fastening board. These markings are intended to provide contrasting detail on an otherwise featureless surface. Utilization of such markings aids orientation of adjacent photographs of a stereopair during setup of the stereodigitizer later on. Figure E.7 is a typical stereopair of the same model section. When these photographs were taken the background contrast was created by attaching a gridded mylar sheet to the wall. In earlier work with the OPS model, targets like the one shown at the top of Figure E.3 were attached *at* random locations on the wall. This was in fact a better approach since there can be no possible movement of the targets between photogrammetric exposures.

[1]A color snapshot is also taken each **time *a*** photogrammetric exposure is taken. The color shots are occasionally used later on to help interpret the black and white photogrammetric exposures.

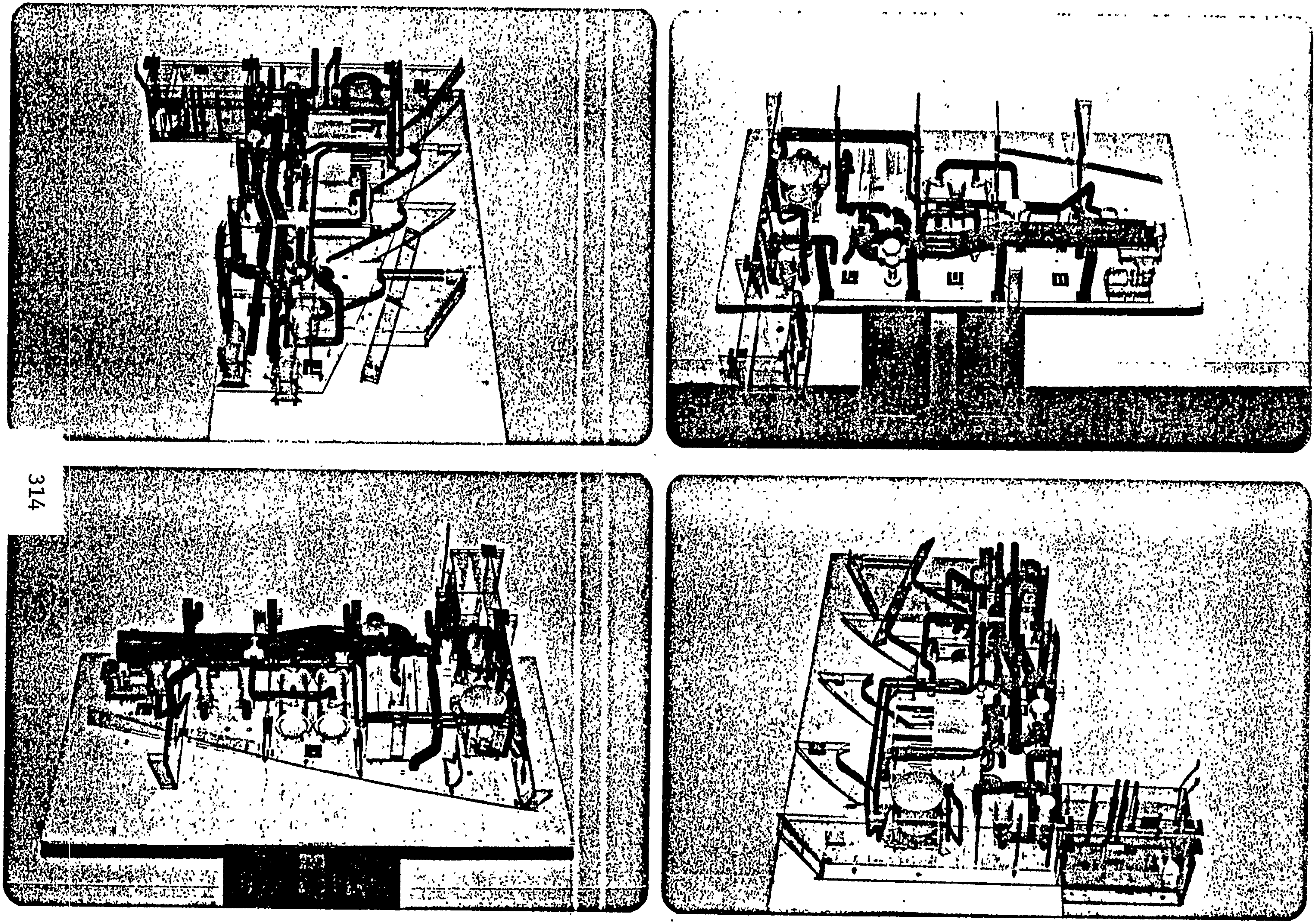


FIGURE E.6: Rotation of a Model Section for Exposing Four Successive Stereopairs. Four views avoid hidden detail, allow digitizing all "sides" of a pipe and permit uniform overall digitizing accuracy.

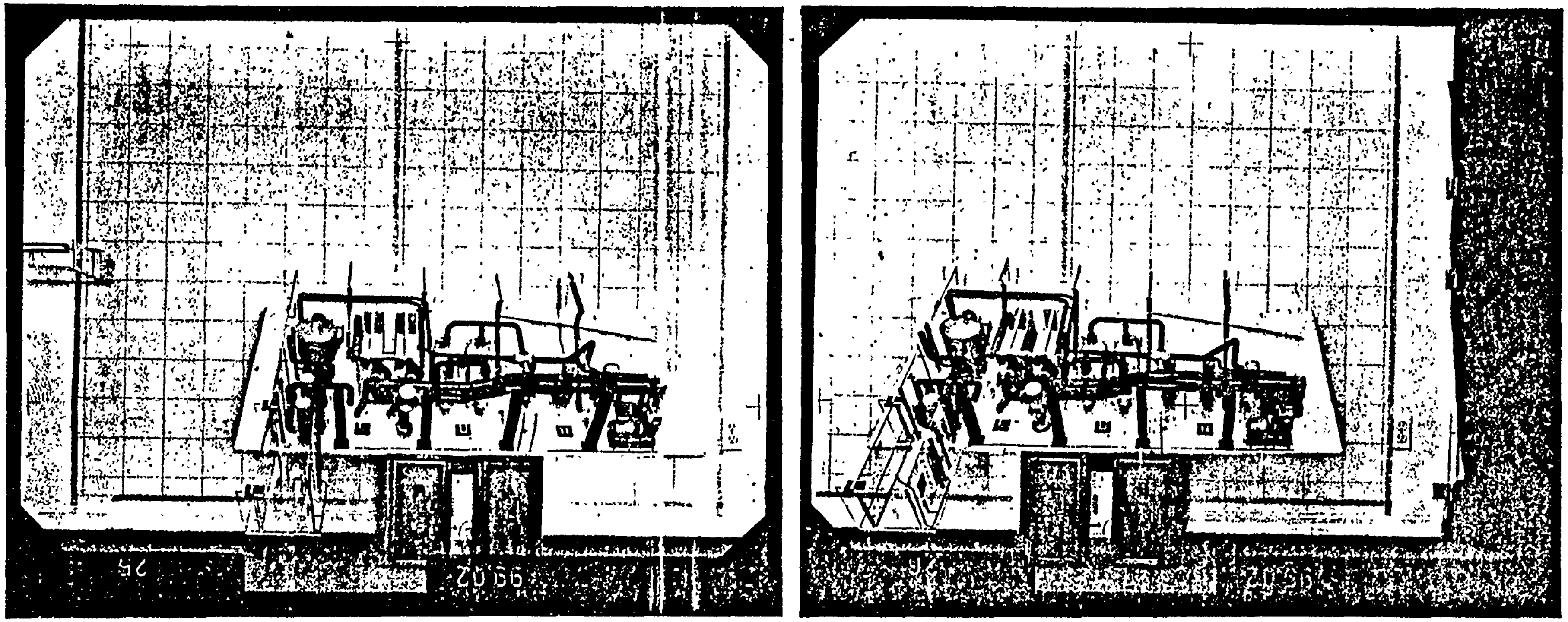


FIGURE E.7: A Typical Photogrammetric Stereopair. The gridded mylar sheet on the wall serves only to provide contrast on an otherwise featureless surface. Photographs are 1:1 prints from the original glass plate negatives.

While it may seem redundant to photograph each model section from four aspects, the process is fast and offers three distinct advantages:

a. It is unlikely that piping detail will be lost entirely. Detail obscured in one or two views will most likely be seen in the others.

b. As indicated earlier, data digitized on a pipe surface will eventually be fit with a cylinder in order to find the true centerline location of the pipe segment. This fitting process is much more reliable when there are data on all "sides" of a pipe segment rather than only on the one side visible in a single stereopair.

c. Data digitized within any given stereopair will have a range of accuracy which decreases from foreground to background detail. If data from all four stereopair are merged, the overall accuracy of all detail digitized becomes more uniform.

E.4.4 <u>Lighting</u>

Bounce lighting of the model is the most desirable. This is accomplished very easily by directing strobe lights toward the walls and ceiling away from the model section. Light impinging upon the model is, therefore, coming from all directions and the resulting negatives are virtually free of shadows. Freedom from shadows is desirable so as to avoid losing detail and also to eliminate the possibility of confusing a pipe's shadow as ***an*** actual pipe.

Because bounce lighting is inefficient relative to direct lighting, it is desirable to employ a fairly high powered strobe unit so that sufficient light can be output in a single pulse: It is also desirable to employ a digital light meter to aid rapid determination of proper exposure without experimenting.

[1]A 1200 watt-second unit was used to light the OPS and Hitachi models.

E.4.5 Emphasis on Simplicity

It is most important to emphasize that all of the above described preparations and procedures are very simple. They can be carried out anywhere without a specially prepared room. Although setup of the proper model/camera geometry is planned in advance, implementation does not require precise measurements; an ordinary carpenter's tape or desk ruler may be used without exercising much care. Bounce lighting is achieved without special precautions in aiming the strobe head(s). Even "eyeball" aiming of the camera is adequate. Figure E.8 illustrates the overall setup for one of the Hitachi model sections. While the setup may appear experimental it need not be any more sophisticated for actual production work.

E.5 Preparation for Stereodigitizing

To permit the operator of the stereodigitizer to rapidly digitize desired data, specific "instructions" should be prepared prior to start-up of digitizing from a given pair of photographs. Such preparation relieves the operator of a multitude of decisions as to what to digitize and what identifiers to attach to digitized data. It also greatly simplifies his housekeeping tasks; e.g. what detail has or has not been digitized. Pre-preparation permits maximum productivity of the stereodigitizer and of the operator's unique expertise to view stereoscopically and digitize in three dimensions.

E.5.1 Photo Enlargements

For familiarization and orientation purposes the operator of the stereodigitizer prefers to have a photographic print from one of the photographs comprising a stereopair to be digitized. Because

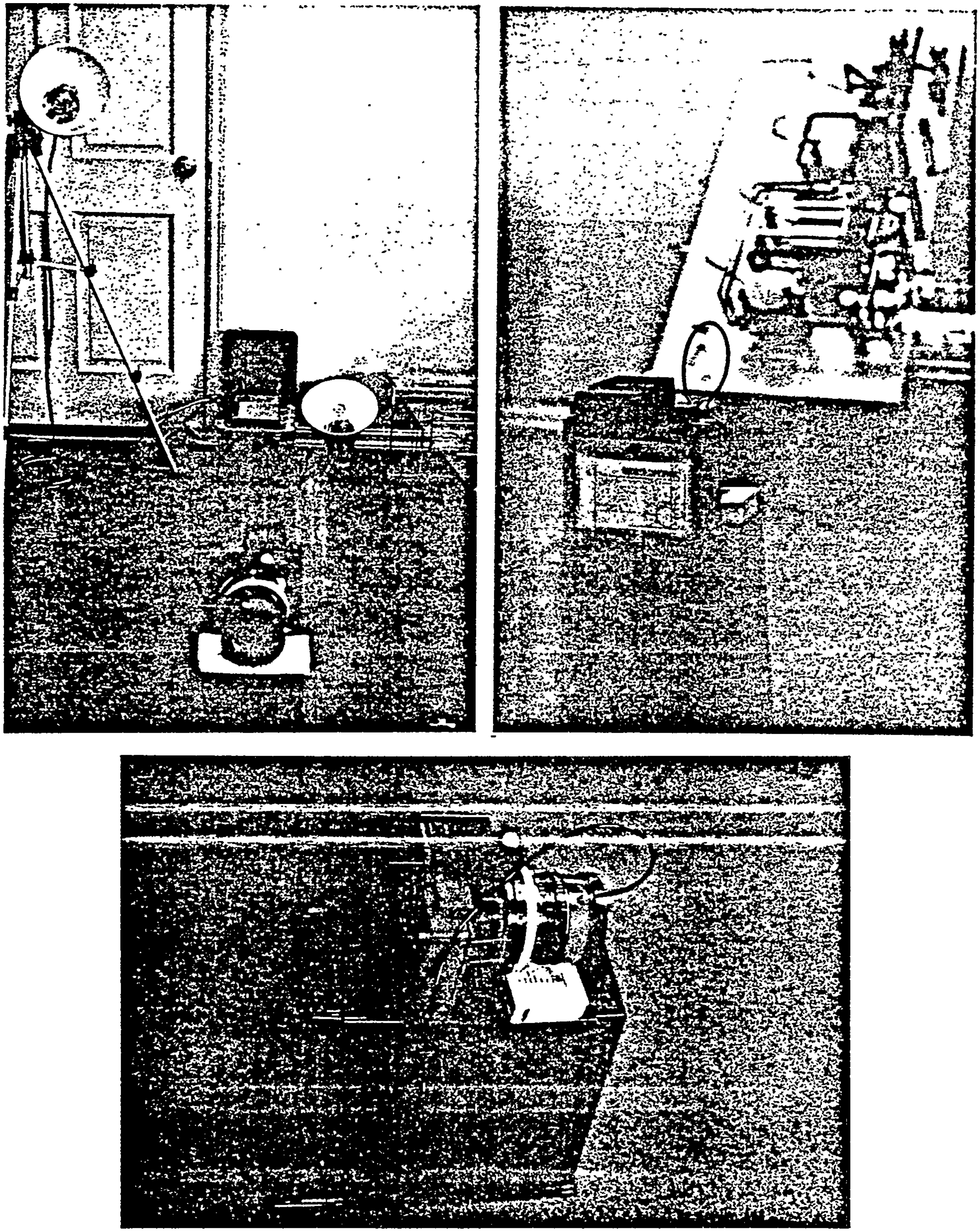


FIGURE E.8: Overall Views of Setup for Taking Photographs of a Typical Model Section. In the upper left the two heads of the ***strobe*** unit are purposely aimed away from the model in order to create "bounce" lighting of the model. The upper right and lower illustrations depict the camera setup. A digital strobemeter rests atop the camera. Note the simplicity of the entire arrangement.

the original negatives are rather small it is preferable to provide him with an enlargement, particularly of just that portion of the negative showing the model proper. Experience has shown that an 11x14 inch enlargement is ideal. This is a practical. size for a photographic laboratory to produce, it is easy to handle and it provides a sufficiently large scale picture of the piping that uncongested line tracings can be prepared in the form of transparent overlays.

E.5.2 Transparent Overlays

Specific detail to be digitized must be identified for the operator of the stereodigitizer. One way in which this can easily be accomplished is *to* mark the detail on transparent overlays[1] to the 11x14 inch enlargements. Four types of detail must be identified:

a. control points; i.e. targets at locations of known ships coordinates (see paragraph E.3.2),

b. tie-in ***points;*** i.e. targets placed ***to*** aid matching of data digitized in different stereomodels (see paragraph E.3.2),

c. pipe surfaces, and

d. pipe events.

Figures E.9 and E.10 respectively show a typical photo enlargement and one of its transparent overlays. The use of colors on the overlay serves no other purpose than to aid the operator of the stereodigitizer in following a given pipe run. Also note that a very simple numbering scheme is employed; one and two digit numbers for targetted points and a pipe

[1]Pipe events are annotated on a separate overlay simply to avoid congestion.

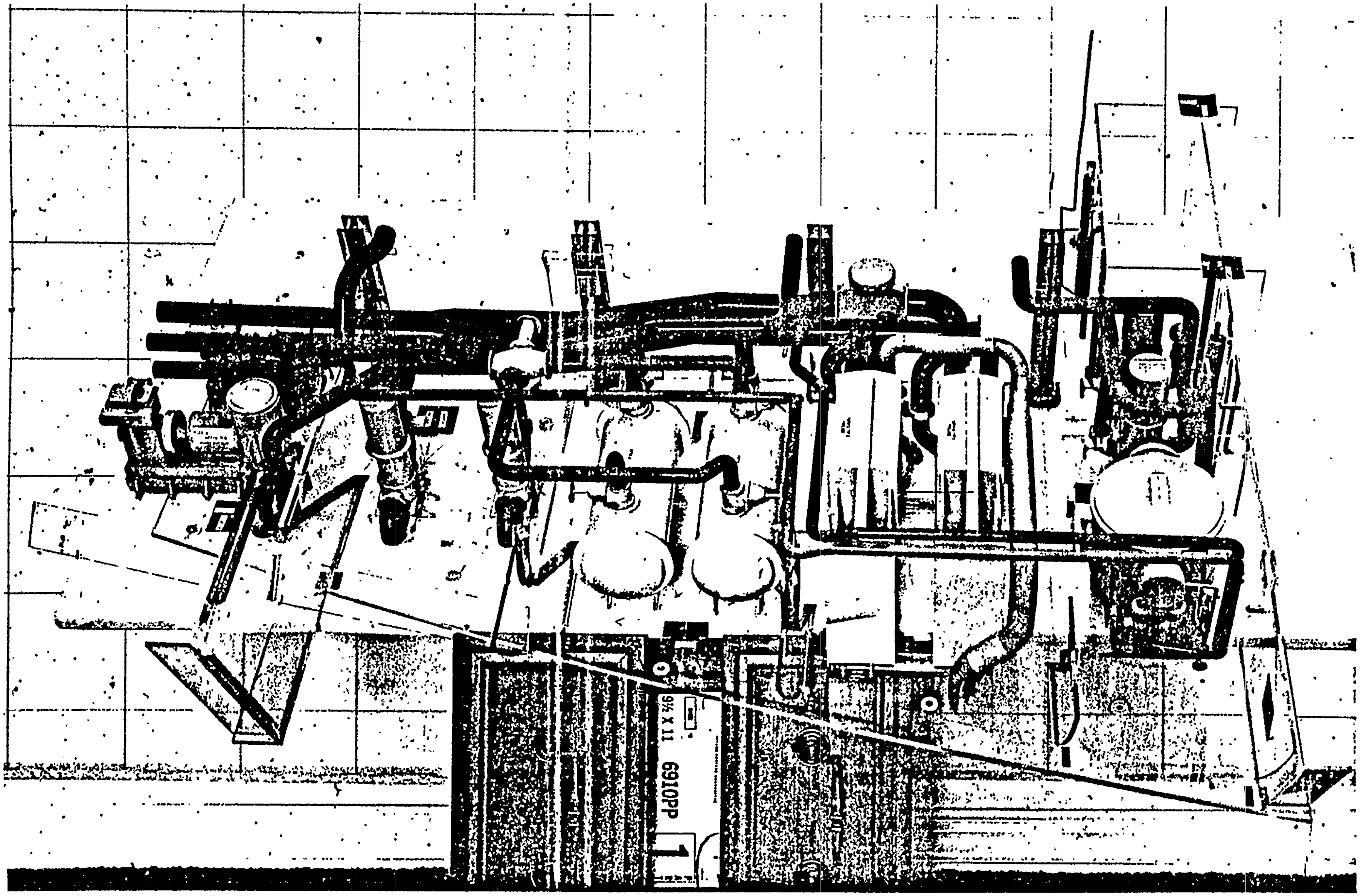


FIGURE E.9: Typical Enlarged Print for Stereodigitizing Preparation

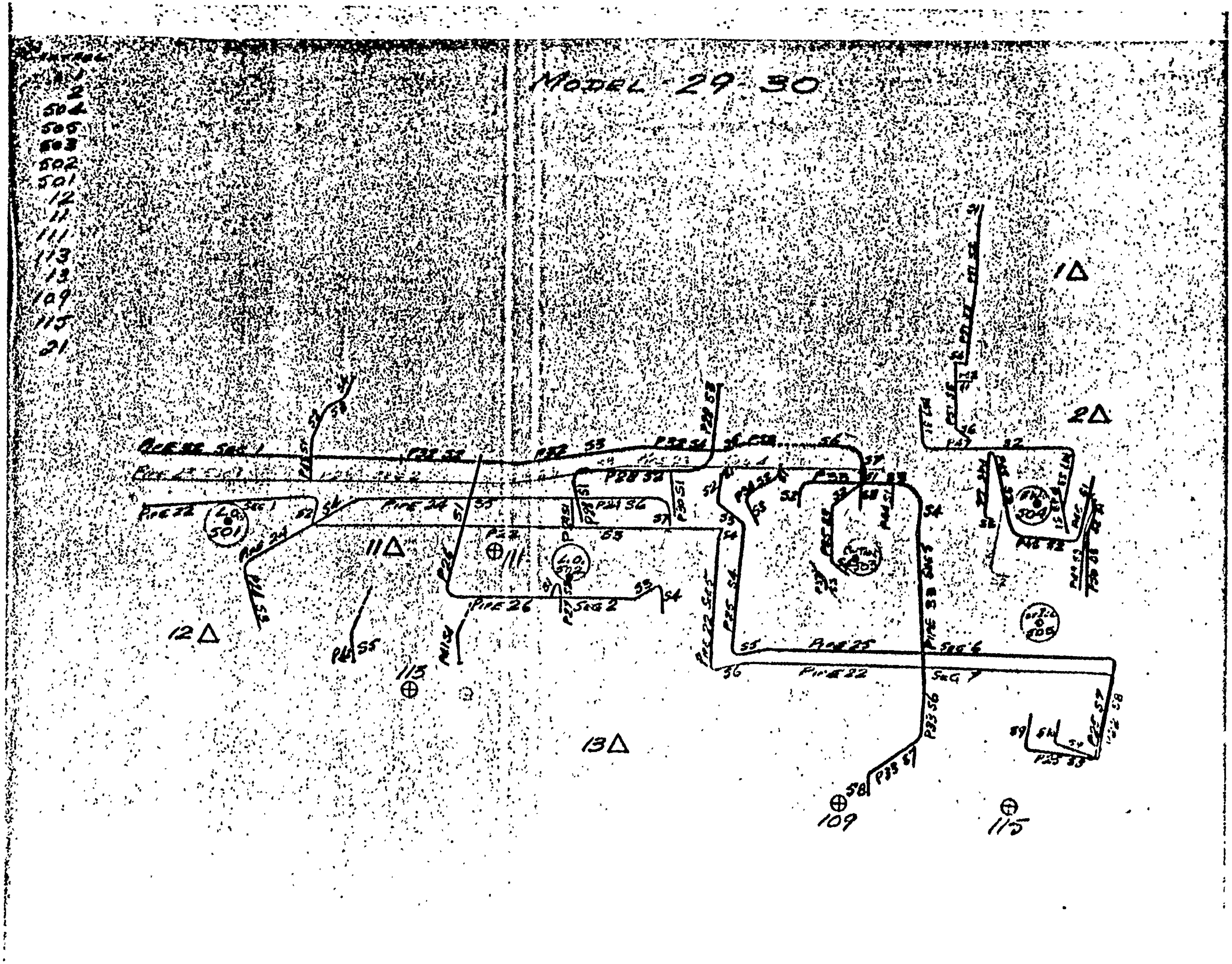


FIGURE E.10: Copy of Transparent Overlay to Enlarged Print Shown in Figure E.9.

number/segment number designation for each straight line portion of a pipe run.

Preparation of overlays is best done by a person familiar with the model. This is because familiarity allows rapid interpretation of a single black and white enlargement for which an overlay is being prepared. (It should be assumed that the model may not be available for other than the picture taking operation.) A person not familiar with the model can also prepare overlays, but more frequent reference *to* the color snapshots will be required.

E.5.3 Precomputing Stereodigitizer Settings

When a pair of photographs are placed into a stereodigitizer, digitizing cannot proceed until the exact position and attitude of one photograph relative to the other is determined first. If the stereodigitizer employed is of the computer-controlled variety, this step can be quickly accomplished by the operator interacting with the instrument's computer. When an analogue stereoplotter is used as the stereodigitizer, this relationship between the photographs must be determined in advance of presenting the photographs to the stereodigitizer.[1] Such predetermined values may be set directly into dials of the analogue stereoplotter.

Because a computer-controlled instrument was not used for this project, precalculation of settings for an analogue stereoplotter was necessary. This involved two steps. First, each of two negatives comprising a stereopair were measured individually on the researcher's monocomparator shown in Figure B.2. Measurements made on each

[1]Theoretically the relationship can be determined empirically at the analogue stereodigitizer. But, this is a very time consuming trial and error process for the type of photographs involved.

negative were simply the locations of a few discrete points (e.g. targets and/or grid intersections on the model and wall behind) whose images appeared on both negatives. In the second step these measurements were processed through an existing computer program to arrive at the needed stereodigitizer instrument settings.

E.6 Stereodigitizing

E.6.1 Hardware

All stereodigitizing work was performed on a Wild AlO analogue stereoplotter like the one shown in Figure B.l. A computer-controlled instrument was preferred, but the AlO was used because of its convenient availability. Bosworth Aerial Surveys, Inc. of Lake Worth, Florida provided valuable man power assistance to the researcher and also made their AlO available for experimental and production work on relatively short notice.

Although Bosworth's A10 is not computer-controlled, it is on-line with a mini-computer. To aid the stereodigitizer operator, programming was prepared by Bosworth to present certain commands or "prompts" to the operator on a CRT beside the AlO. Answers to these prompts are entered on the keyboard of the CRT by the stereodigitizer operator. These data plus XYZ coordinates digitized by the operator while viewing the stereomodel are automatically fed directly to the mini-computer and stored on a disc. Inasmuch as the researcher's computer is practically identical to Bosworth's, transfer of data to the researcher's facility for subsequent data processing was simply a matter of hand carrying a disc cartridge.

E.6.2 Digitizing Sequence

Because of preparations made in advance (see paragraph E.5) the stereodigiting work is rather routine and proceeds rapidly.

For each' stereomodel the following sequence is typical:

a. load glass plate negatives in photo carriers of the stereodigitizer

b. manually dial precomputed instrument ***settings*** into the stereodigitizer (see paragraph E.5.3)

C. make fine adjustments to the precomputed settings while visually inspecting the stereomodel

d. initialize the prompting program from the CRT keyboard and answer questions such as stereomodel number and types of detail to be digitized first

e. digitize each targetted point; enter its number via the CRT keyboard, find the point in the stereomodel and depress the "record" foot pedal

f. advise the prompt program, via the CRT keyboard, that pipes will be digitized next

g. enter the pipe number at the CRT keyboard

h. enter the first segment number at the CRT keyboard

I. Digitize points on the surface of the pipe segment

j. repeat steps h and I for as many additional segments of the present pipe run that are visible in the current stereomodel

k. repeat steps g through j for all remaining pipe runs within this stereomodel

1. advise the prompt program that events will be digitized next

m. advise the prompt program of the pipe and segment number for which events will be digitized

n. advise the prompt program of the event number to be digitized

0. digitize either one or two points on the present event

P. repeat steps n and o for as many additional events on the present pipe segment that are visible in the current stereomodel

q. repeat steps m through p for all remaining pipe segments having visible events

r. advise the prompt program that the current stereomodel is completed

E.6.3 Specific Procedures for Pipe Segments

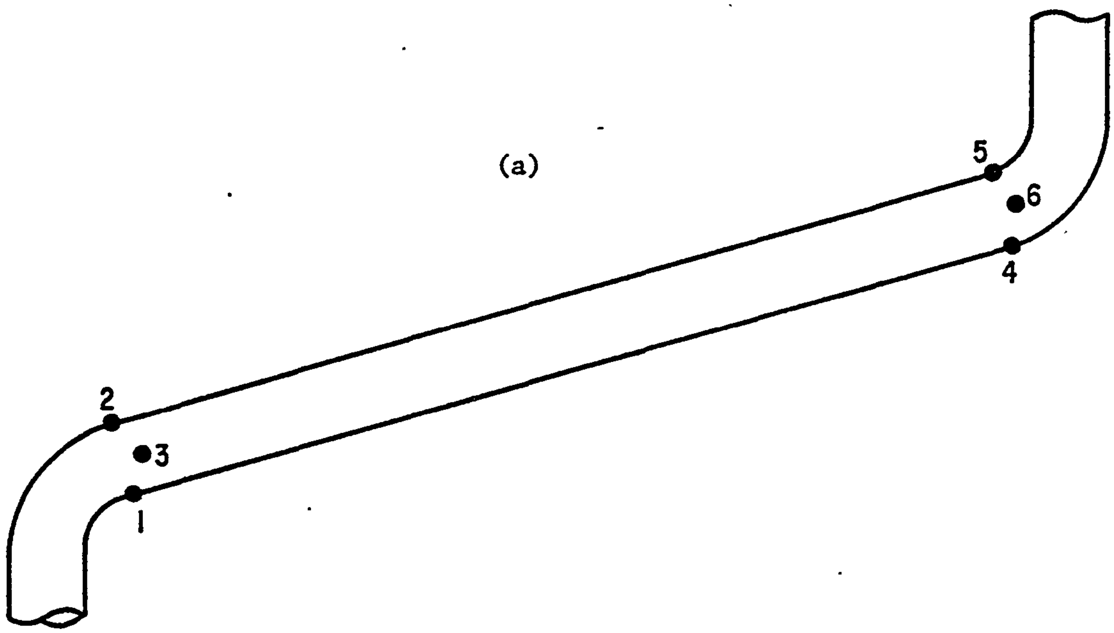
when digitizing a pipe segment it is preferred to read six points (within each stereomodel in which the segment appears) in the approximate locations shown in Figure E.lla. The notion of "approximate" is emphasized since obscurations by other detail of the model oftentimes dictate deviations from this scheme. Later on in the data processing a cylinder is fit to all points digitized on a pipe's surface in order to find the location and orientation of the centerline of the segment. That program makes no rigid assumptions as to the locations of digitized points, but it does use the ordering of the first points encountered for a pipe segment as follows:

a. points 1 and 2 are used to obtain an estimate of the diameter of the pipe segment

b. points 1 and 4 are used to obtain an estimate of the location and orientation of the segment

Estimates obtained in this way are then refined in the cylinder fitting process. Because of obscurations, actual locations of digitized points could be as shown in Figure E.1l.b. Note that approximations for diameter, location and orientation can still be obtained.

It is *a* matter of practical importance that digitized points be reasonably close to their respective bend intersection points. This is because the points of real interest, i.e. the bend intersection points themselves, will eventually be computed by intersecting calculated centerlines of adjacent pipe segments. The accuracy of the calculated centerlines will be greater if cylinders are fit to widely separated (lengthwise) digitized points. Theoretically the accuracy would also be higher if additional points



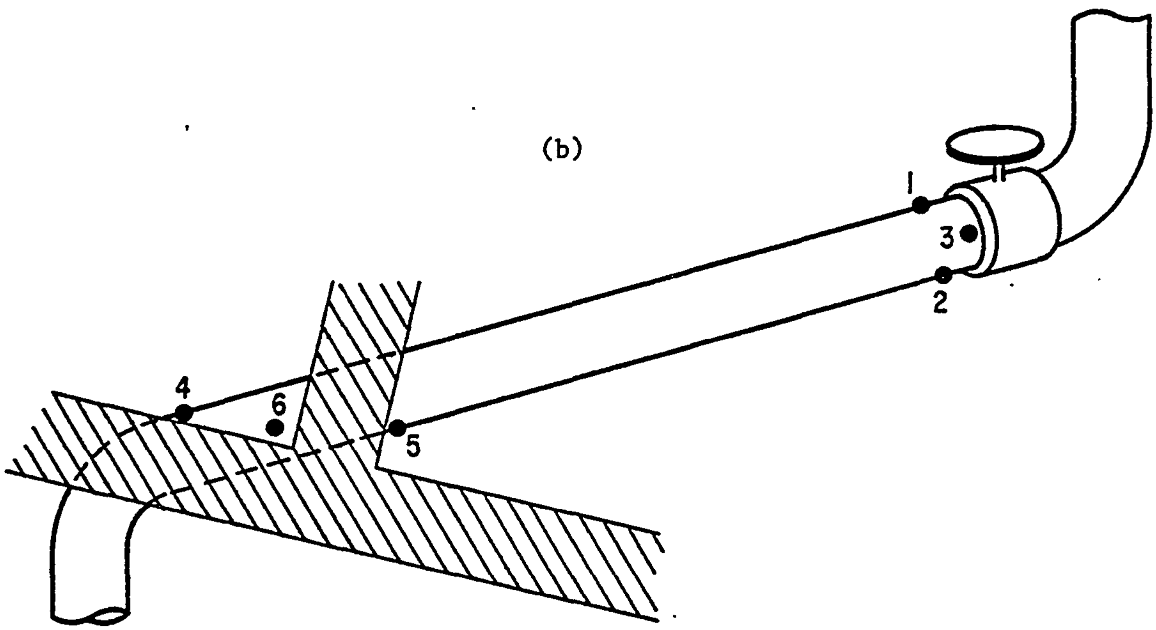


FIGURE E.11: Approximate Locations of Points Digitized on a Pipe Segment. The upper figure indicates ideal locations, in any one stereomodel, near the ends of the segment. As a practical matter, data are taken wherever the pipe segment is visible such as in the lower figure.

are digitized. But, the obvious choice of locations for such additional points, i.e. approximately midway along a pipe segment, usually works to the detriment of the process. Curvature in a modeled pipe, particularly a long run of small diameter, invalidates the concept of cylinder-fitting.

E.6.4 Specific Procedures for Pipe Events

Unlike pipes, pipe events are usually digitized only in one stereomodel rather than four. Decisions as to which events are to be digitized in which stereomodels are made at the preparation stage. Since surfaces are not fit to pipe events in the data processing stage, there is no need to digitize data on all 'sides' of an event.

Only one or two points are digitized on each event. The data processing program simply constructs a line in space through the digitized point(s) such that the line is perpendicular to the previously computed location and orientation of the pipe segment to which the event belongs. For an event with a single digitized point, the location at which the perpendicular strikes the centerline is the centerline location of the pipe event. If an event has two digitized points the program averages the two results. This computational scheme implies, therefore, that the operator of the stereodigitizer decides whether an event may be a "one point event" or a "two point event". With this.freedom of choice the operator can digitize an event such as a symmetrical valve with a stem simply by digitizing one point on the stem. Other symmetric events without such a center-defining feature are digitized as two point events; one point on each of two symmetrically located (lengthwise along the pipe) faces and/or edges.

E.7 Data Processing

Of necessity many details of the data processing functions have already been explained because they directly influenced all prior tasks from preparation of the model through stereodigitizing. Hence, following discussions of the data processing steps are expanded only to the extent deemed necessary to understand the logical progression of the calculations.

For each model section the data processing steps proceed in the following order:

a. By means of a three dimensional coordinate transformation program, all digitized data in stereomodel number two are put into the coordinate system of stereomodel number one. Similarly, data for stereomodel number three are put into the coordinate system of stereomodel number one and data for stereomodel number four are put into the coordinate system of stereomodel number one. This step is required because each view (stereomodel) of a given model section is digitized in its own arbitrary coordinate system whereas all data from all four stereomodels eventually need to be in a single common coordinate system.

   The basis for transforming data from one stereomodel to the coordinate system of another is by best-fitting the two sets of data at the tie-in targets common to both sets of data. This transformation process is actually comprised of two distinct steps. First, considering only the tie-in targets common to the two sets of data, the program determines seven transformation constants (3 shifts, 3 rotations and a scale factor) which, when applied to the second set of data, will convert it to the coordinate system of the first set of data in such a way as to minimize any remaining differences between coordinates of tie-in targets in the first set of data and transformed coordinates of tie-in targets in the second set of data. Once the seven constants are determined, they are then applied to all data in the second set so as to convert them into the coordinate system of the first set of data.

b. By means of the same three dimensional transformation program described above, all data resulting from step "a" are transformed into the ship's coordinate system. The seven transformation constants are determined by best-fitting coordinates (from step "a") of the targetted grid intersection points to the known or true ship coordinates for these grid intersections. Once the transformation constants are determined they are applied to all data from step "a" to produce ship's coordinates for every digitized point.

see paragraph E.3.2.

c. At this point in the data processing the data, even though in a common (i.e. ship's) coordinate system, are very disorganized. Hence, the next data processing step is to reorder the data so that all data belonging to a given pipe segment are collected together. This is merely a sorting operation; no calculations are performed with the data.

d. Now that all data belonging to a given pipe segment are collected together, they are input to a cylinder fitting program whose primary function is to determine the location and orientation of the centerline of the cylinder which best-fits all points belonging the particular pipe segment being processed. The basis for the calculation is that of finding the radius and centerline location and orientation of a perfect cylindrical surface which minimizes the perpendicular departures of the points from the perfect surface. Computed centerline locations and orientations for all pipe segments are stored in a separate data file for subsequent use in the next two data processing steps.

e. Wherever there are two adjacent centerlines of segments belonging to the same pipe run, the segments are numerically extended in three dimensional space so as to find their point of intersection. To be more correct, this "intersection" is actually the point of closest approach since it is unlikely that two lines in three dimensional space will intersect exactly. The calculated intersection point is the so-called bend intersection point and- is one of the principal end products desired of the photogrammetric dimensioning process (see paragraph 1.5). Figure E.12 illustrates how bend intersection points are calculated.

f. Centerline locations of pipe events are considered next. Data (after step b) belonging to a given event are matched with centerline data contained in the data file created in step d. This is done simply by finding the proper pipe/segment number in the centerline data file. Computation of the centerline location of the pipe event then proceeds as described in paragraph E.6.4. These locations are the second principal end products desired of the photogrammetric dimensioning process (see paragraph 1.5).

E.8 Evaluation of End Results

Experimental stereodigitizing was performed with the oPS model on two different occasions. Two different digitizing sessions were also conducted using the Hitachi model. Although all six sections of the Hitachi model were not entirely digitized, data collected and experience gained were adequate to draw definite conclusions.

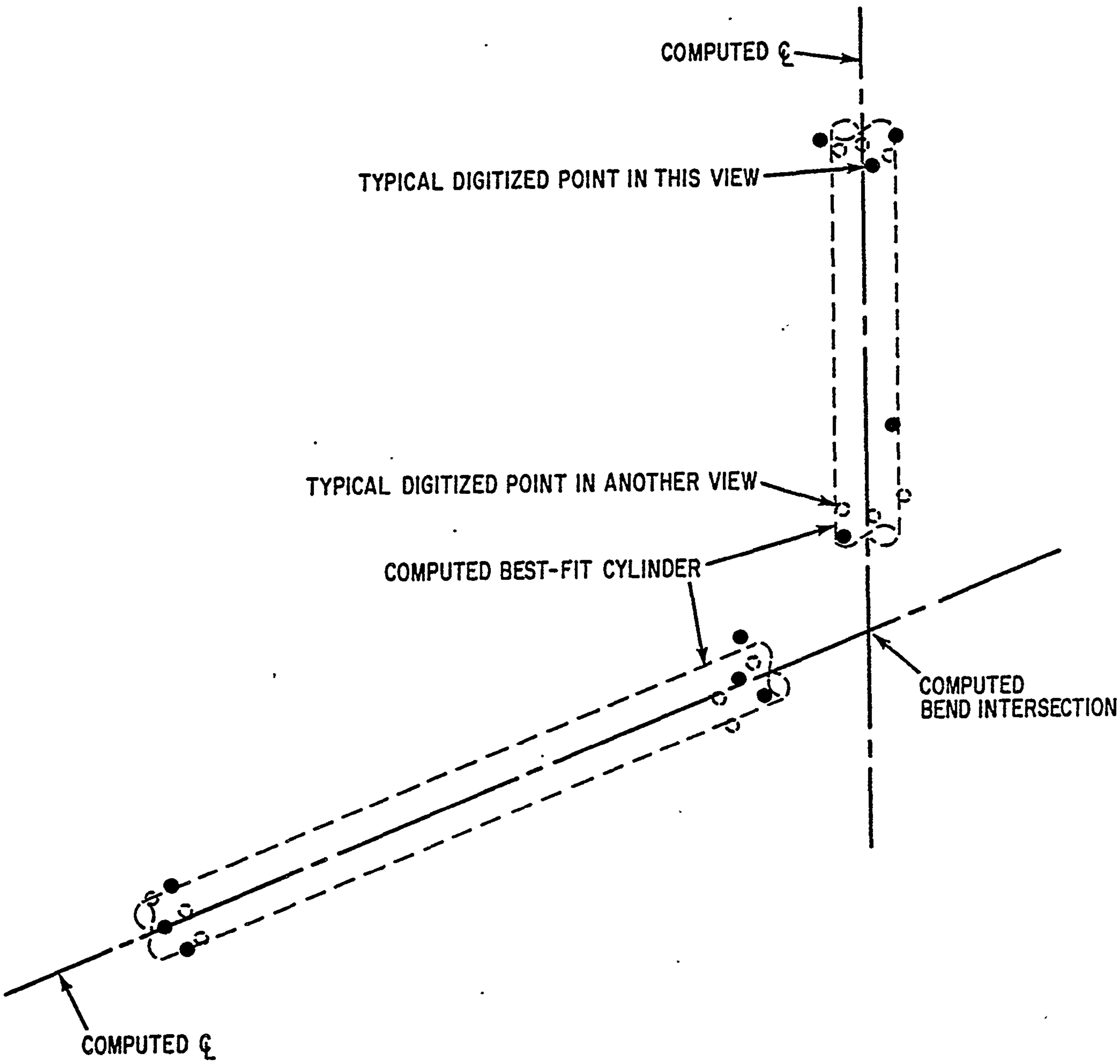


FIGURE E.12: Illustrating How Bend Intersection Points are calculated. A cylinder is best-fit to digitized points on a pipe segment to find the location and orientation of its centerline. Centerlines of adjacent pipe segments are then extended to find the bend intersection point. Although the illustration is two dimensional, digitizing and calculations are performed in three dimensional space.

E.8.1 Accuracy

One means for assessing the accuracy of data derived from the photogrammetric process was to calculate space distances between adjacent bend intersection points in the same pipe run. That is, computed XYZ coordinates of adjacent bend intersection points (Figure E.12) were used to compute the distance between the points. The same distances were also scaled by hand directly from the model and then compared to the calculated values.

Initial comparison of computed versus manually measured distances were astonishing. Despite particular care in taking the manual measurements it was found that they were replete with blunders of various sorts. Nearly every one of the errors, however, were directly traceable to the fact that pipe lengths cannot be directly measured by hand on the model. In the best of instances such as two adjacent 90 degree bends with no obstructions to hinder manual measurement, it is still necessary to apply a correction for the diameter of the pipe[1] and to scale the measurement to on board length. Even these two seemingly simply corrections were sometimes made incorrectly or forgotten altogether. As a practical matter, most distances are much more difficult to measure because of congestion within the model. This introduces the need to measure to offsets and/or to accumulate partial length measurements, each admitting additional chances for error. Finally, the most persistent cause for error in manual

[1]Because, for example outside of bend to outside of bend is measured.

measurements was associated with bends other than 90 degrees, particularly shallow bends. Because such bend intersection points are physically non-existent in the model and because they cannot be inferred as accurately as a 90-degree bend, the manual measurement' is virtually to an estimated location for the bend intersection.

After rectifying errors in the manual measurements as best as possible, differences between 86 photogrammetric and manually obtained distances between bend intersection points averaged 8.4 mm (0.33 inch) with a maximum difference of 40.0 mm (1.57 inch) on board. Because the manual measurements are still of questionable accuracy to be used as a base for comparison, it is fair to state that the actual accuracy of the photogrammetric results is quite likely to be better than the reported average and maximum differences.

'A similar comparison scheme was employed for pipe events. Computed XYZ coordinates of the centerline location of a pipe event and computed XYZ coordinates of the nearest in-line bend intersection point were used to compute the distance from the bend intersection point to the event. Twenty-four such distances, when compared to the same distances obtained by manual measurement of the model (after corrections for blunders) revealed an average difference of 12.6 mm (0.50 inch) and a maximum error of 28.0 mm (1.10 inch). As in the case of pipe lengths, the photogrammetric data are probably better than these figures might imply.

E.8.2 Completeness

The photogrammetric scheme outlined in this Appendix allows four chances to capture data for any pipe segment or event even though it may be partially obscured in all four instances (i.e. all four stereomodels). Moreover, there are no rigid requirements[1] as to where data must be taken in any one of these views. Because of this general approach-to the problem, virtually all piping detail can be dimensioned by the photograrommetric process. Even if an occasional detail is not captured, this presents no significant difficulty because provision has been made to permit merging manual measurements or .a-priori knowledge of such detail into the computer data files.

E.8.3 Cost (Circa August 1980)

By extrapolation of experience with the Hitachi model it is projected that piping geometry for all six model sections (Figure 2.1) can be produced for $12,100 excluding G&A and profit. This figure covers labor and expenses for all phases of the work from photography through data processing. Data for approximately 230 pipe segments and 160 pipe events would be the end products.

It must be emphasized that the above projection is based upon utilization of the system described in this Appendix. As has already been stated, use of the Wild Al0 as the stereodigitizer was a matter of convenience (paragraph E.6.1). Had a computer-controlled instrument such as the one shown in Figure E.13 been employed, the total cost for producing data for all six model sections is estimated to be about 25% less. Table E.1 summarizes costs by tasks depending upon which type instrument is employed.

[1] But, there are preferred locations.

TABLE E.1

Projected Costs for Photogrammetric Dimensioning of the Hitachi Model Shown in Figure 2.1

Task	Cost With Analogue Stereodigitizer	Cost With Computer-Controlled Stereodigitizer
Photography	$ 1,405	$1,405
Precalculate Settings	2,955	N/A
Preparation and Digitizing	5,300	5,300
Data Processing	2,440	2,440
TOTALS	$12,100	$9,145

It is also significant that the first cost for hardware is significantly different for the analogue and computer-controlled stereodigitizer systems. The more productive computer-controlled system is also cheaper by a factor of nearly two owing to the fact that it does not require a comparator for precalculation of instrument settings and that its computer can be used for data processing as well as operation of the stereodigitizer itself. Table E.l summarizes hardware costs.

E.9 Concluding Remarks

The photogrammetric system and procedures described in this Appendix certainly confirm that photogrammetric dimensioning of distributive systems models is practical, particularly in view of alternate methods described in Appendix D. It must be said,,however, that variations of photogrammetric procedures described are entirely feasible. That is, the described procedures are not necessarily the only ones which will produce acceptable end products.

TABLE E.2

First Costs for Photogrammetric Hardware

Item	Analogue Stereodigitizer System Used on this Project		Computer-Controlled Stereodigitizer System	
Camera	Wild P31 (Fig. E.4)	$ 23;000	Zeiss Jena (Para. E.4.1)	$ 30,000
Comparator	Kern MK2 (Fig. B.2)	28,000		N/A
Mini-Computer	Data General or Digital Equip. Corp.	28,000		N/A
Stereodigitizer	Wild A10 (Fig. B.1)	190,000	Bendix US2 (Fig. E.13)	110,000
TOTALS		$269,000		$140,000

Because the basic objective of this project is to demonstrate the practicality of photogramnetric dimensioning, many small details, which must eventually be considered in production work, have been ignored. For example, computation of flange orientations, in-line discontinuities such as reducers, data validation checks, etc. These are viewed as being data processing functions which need not be addressed within the scope of this project. It is clear by now that photogrammetry provides a viable three dimensional digitizing process that can generate all data needed to satisfy all subsequent data processing functions.

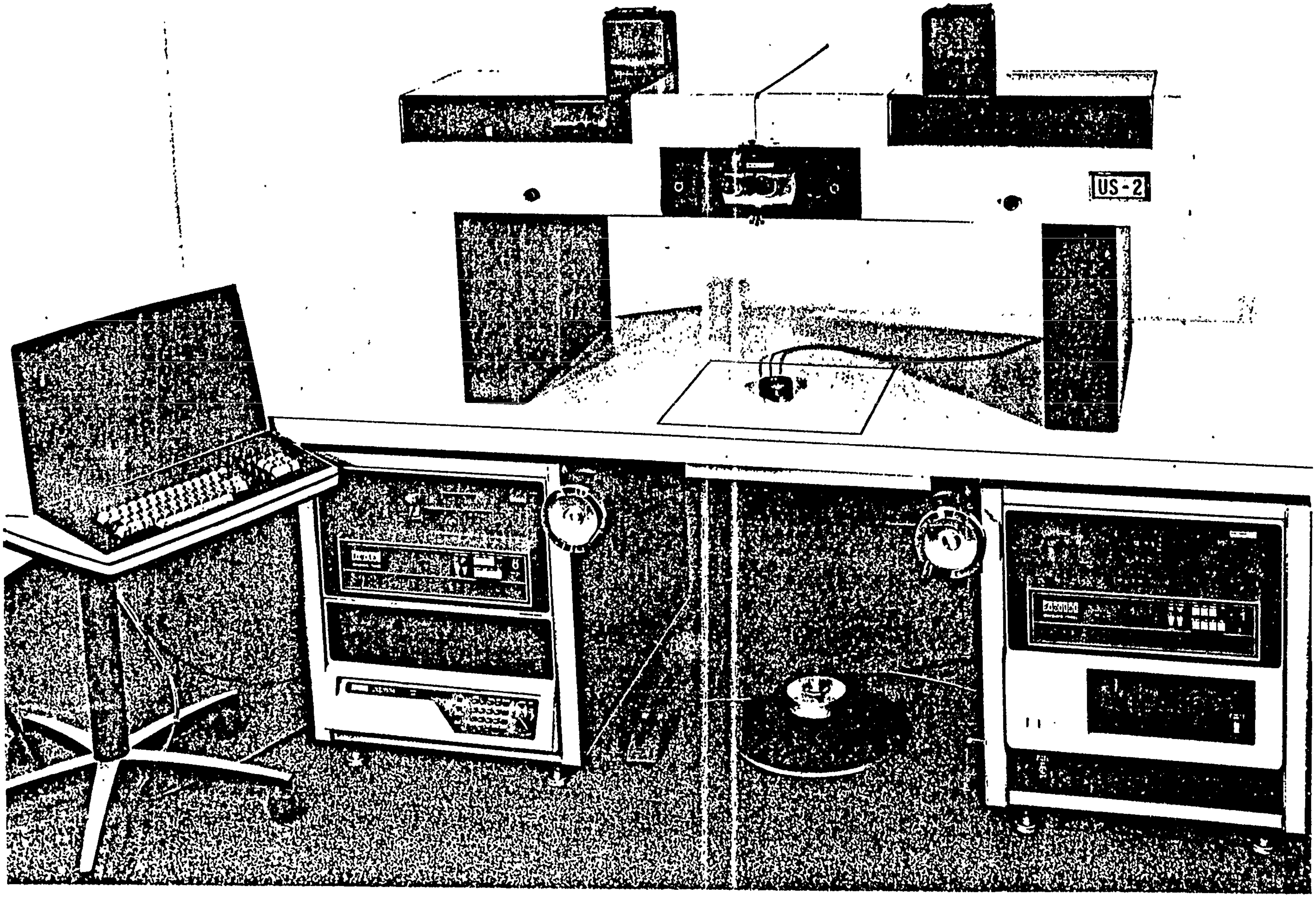


FIGURE E.13: A Computer-Controlled Stereoplotter. A mini-computer (set within legs of the instrument) numerically handles functions performed by mechanical solutions of the analogue variety of stereoplotters. Data are recorded on the computer's discs. The particular instrument shown is the US2; photograph courtesy of Helava Associates, Inc.

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